Strong, Ultra-narrow Peaks of Longitudinal and Hall Resistances in the Regime of Breakdown of the Quantum Hall Effect

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With unusually slow and high-resolution sweeps of magnetic field, strong, ultra-narrow (width down to 100 μT) resistance peaks are observed in the regime of breakdown of the quantum Hall effect. The peaks are dependent on the directions and even the history of magnetic field sweeps, indicating the involvement of a very slow physical process. Such a process and the sharp peaks are, however, not predicted by existing theories. We also find a clear connection between the resistance peaks and nuclear spin polarization.

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The integer quantum Hall effect (QHE) is a most remarkable phenomenon of two dimensional electron system (2DES), in which the Hall resistance is quantized to h/ie^2 while the longitudinal resistance nearly vanishes (h is Planck's constant, e the electron charge, and i an integer) [1]. To employ the QHE for the resistance standard, it is desirable to apply a high current through a Hall bar. However, it was early discovered that the QHE breaks down if the current reaches a critical value, I_c [2,3]. Extensive investigations were thereafter performed to study the origin of the breakdown [4–15]. So far, most studies have focused on factors that influence the critical current around, in particular, even filling factors. A number of models have been proposed, such as inter-Landau-level scattering [4,7] and the superheating process [2,5]. However, the exact mechanism responsible for the breakdown is still under debate.

Here, we report on the measurement of the *differential* longitudinal and Hall resistances R_{xx} and R_{xy} (the derivative of voltage with respect to the total applied current) at high injected currents close to I_c. With unusually slow, high-resolution sweeps of magnetic field B, ultra-narrow R_{xx} peaks (width down to 100 μT) are observed. The peak values exceed the resistances of the surrounding magnetic fields by a factor 36. While no substantial change in R_{xy} is noticed around the odd filling factor $\nu = 3$, strong, sharp peaks are also shown on the R_{xy} curves for $\nu = 2$ and 4. We find the peaks to be sensitively dependent on the directions and even the history of the B sweeps. This indicates that a physical process with a very large time constant is involved, which is orders of magnitude longer than that may be predicted by the existing models for the QHE breakdown. While many *disordered* electronic systems have recently been found to exhibit very slow relaxations [16], to our knowledge, the unusually slow physical process to be reported here has never been observed in the integer QHE regime. Interestingly, some of the aspects of our experimental observations are similar to the discovered anomalous resistance peaks in the *fractional* QHE regime [17], while some other aspects are apparently different. We will also show that the sharp resistance peaks are influenced by the nuclear spin flips. Furthermore, we present a model, which qualitatively explains the different aspects of our observations.

We use two GaAs/AlGaAs modulation-doped heterostructures (wafer I and wafer II) with carrier densities of $n_s = 3.7$ and 3.5×10^{15} m^{-2} and mobilities of $\mu = 59$ and 130 m^2/Vs at 0.3 K, respectively. A modulation-doped $In_{0.75}Ga_{0.25}As/InP$ structure ($n_s = 2.8 \times 10^{15}$ m^{-2}, $\mu = 22$ m^2/Vs) is also studied. For all these wafers, I_c is found to scale linearly with the device width. The experiments are performed in a ^{3}He refrigerator at 0.3 K. Hall devices with different widths (from 43 to 200 μm) and different geometries are investigated using a standard lock-in technique with a frequency of 17 Hz. Together with a 5 nA ac current, large dc currents, I_{dc}, are sent through the sample to drive the 2DES close to the regime of breakdown of the QHE. Qualitatively similar behavior is observed in all the samples fabricated from different material systems. We report here on measurements performed on a Hall bar made from wafer I.

The inset of Fig. 1(a) shows the curves of differential resistances R_{xx} and R_{xy} as a function of B around $\nu = 3$ and at a dc current close to, but below, the critical current $I_c = 11$ μA. The Hall bar has a width of 43 μm and five pairs of voltage probes, as is schematically shown in the inset of Fig. 1(b). The B sweep is at a "normal" speed of 0.14 T/min and the curves are "as expected", i.e. R_{xx} nearly vanishes and $R_{xy} = h/3e^2$ within a B range (i.e. the dissipationless regime) that is narrower than that at $I_{dc} = 0$. However, by reducing the sweep speed and increasing the magnetic field resolution, the two R_{xx} peaks at the left and right edges of the dissipationless regime become successively higher and narrower. Furthermore, the curves of the upward and downward sweeps become increasingly different. Figure 1(a) shows the differential resistances around the left edge of the dissipationless regime at a sweep speed of 0.13 mT/min and a sweep step of 0.000015 T, which is the resolution of our

magnet system. The arrows on the curves indicate the sweep directions. While the downward sweeps show only very small changes in R_{xy}, strong peaks are observed on the R_{xx} curve. The narrower peak has a full width at half maximum (FWHM) of only 100 μT. The resistance value at the peak is almost four times as high as the value at the Hall plateau and about 36 times higher than the R_{xx} value on the lower B side. For lower magnetic fields, R_{xx} is found to remain virtually constant [18]. When sweeping upwards from 5.03 T, however, R_{xx} remains at this constant value (no peak structures) until it suddenly drops to zero at about 5.048 T. The behavior is thus totally different from the hysteresis effect of the breakdown of the QHE [2,3] where only a shift in the magnetic field position is observed.

We have simultaneously measured R_{xx} using different segments of the Hall bar. Figure 1(b) shows the results of a downward sweep within 2 mT, using probes 1 and 2, 2 and 3, and 4 and 5. We obtain almost identically strong, narrow resistance peaks from different parts of the Hall bar. For instance, it can be seen in Fig. 1(b) that the peak on the higher field side has a fine structure, which can be seen on all the three traces. This rules out the possibility that our observations are due to local breakdown induced by inhomogeneities of the sample. Further studies of the fine structure, however, require a magnet system with a better resolution. The behavior of R_{xx} and R_{xy} at the higher B edge of the dissipationless regime is very similar to that shown in Fig. 1. There, an upward sweep results in sharp R_{xx} peaks while a downward sweep shows only a sudden drop to zero.

If I_{dc} is decreased, the height of the R_{xx} peaks is reduced, while the width increases. Furthermore, there is less difference in the R_{xx} curves between upward and downward sweeps. Figure 2 shows the R_{xx} traces obtained from different segments of the Hall bar at a lower current, $I_{dc} = 9.5$ μA. The B range corresponds to the right edge of the dissipationless regime around $\nu = 3$. Five successive sweeps [Figs. (a)–(e)] are made back and forth between 5.160 T and 5.175 T with a speed of 0.3 mT/min. The curves are plotted only in the range between 5.1625 T and 5.1690 T for clarity. The change in the peak position of about 3 mT with sweep direction is most likely due to hysteresis of the magnet system. Although each sweep takes about one hour, the peak structure changes gradually, indicating the involvement of a very slow physical process. We have noticed the following points. First, curves obtained in the same sweep direction, such as Figs. (a), (c), and (e) or Figs. (b) and (d), are similar. Second, the greater the number of sweeps made, the less the difference in the R_{xx} curves between upward and downward sweeps. This can already be seen from the increased similarity between Figs. (d) and (e), and is more clear in later sweeps (not shown here). Third, an increasing number of peaks and fine structures are obtained when more sweeps are made. This rules out any trivial heating effects, as heating is expected to smear out fine structures.

Although strong peaks are observed on the R_{xx} curves, the Hall resistance around $\nu = 3$ shows only small changes as can be seen in Fig. 1(a). The behavior of R_{xy} around the even filling factors $\nu = 2$ and 4 is, however, totally different. This suggests that the phenomenon is connected with the spin of the 2DES. Figure 3 shows three R_{xx} traces taken from different segments of the Hall bar and one R_{xy} curve around $\nu = 2$. The dc current is 24 μA, which is about $I_c/2$ at this filling factor [19]. The B range is centered at the right edge of the dissipationless regime. In contrast to the results for odd filling factors [see Fig. 1(a)], an equally strong, narrow peak (FWHM below 3 mT) forms on the R_{xy} trace as on the R_{xx} traces. The peak value is more than five times higher than the Hall plateau $h/2e^2$.

It can be observed that R_{xx} becomes negative on the higher B side of the peaks in Fig. 3. A dc measurement of the longitudinal resistance is shown in the inset. Obviously, dc resistances can be quite different from differential resistances in the nonlinear regime. This is the reason why no anomalous behavior is observed in the dc measurement at 8.1354 T where sharp peaks form on the differential resistance curves. In fact, we do not see any unusual behavior of the dc resistance at other B values.

The general features reported here are observed at all filling factors at sufficiently high magnetic fields and in all the Hall bars and wafers studied. Thus, the above phenomena seem to be general in 2DES. The fine structures are, however, very difficult to fully reproduce in different samples. This is, at least in part, due to the fact that the fine structures are extremely sensitive to the exact I_{dc} used, sweep speed, starting point of sweeps, history, etc.

While many disordered electronic systems are characterized by very slow relaxations [16], to our knowledge, the above unusually slow physical process has never been observed in the integer QHE regime. It is orders of magnitude slower than the time scale of the instabilities in the regime of the QHE breakdown [3,8,9]. The existing models for the breakdown of the QHE, such as inter-Landau-level scattering [4,7] and electron superheating [2,5], do not predict any physical process with a time constant larger than microseconds. Interestingly, we have noticed that certain aspects of our observations, such as the long time constant, strong R_{xx} peaks, and current dependence, are similar to the recently discovered anomalous resistance peaks in the *fractional* QHE regime at $\nu = \frac{2}{3}$ and $\frac{3}{5}$ [17]. However, some other aspects are different, such as the existence of fine structures, strong R_{xy} peaks, the much sharper peaks (more than three orders of magnitude narrower), etc. Very recently, the peaks observed in Ref. [17] were found to be influenced by the nuclear spin polarization [20]. We have also performed nuclear magnetic resonance (NMR) experiments on ^{75}As,

^{69}Ga, and ^{71}Ga. A typical result for ^{75}As is shown by the lower inset in Fig. 1(b). The splitting of the line is, however, threefold that is different from the fourfold splitting observed in Ref. [20]. Furthermore, we observe resonance peaks rather than dips as in Ref. [20]. While the above NMR response is strong in the GaAs/AlGaAs samples, so far, no clear observation has been obtained in our InGaAs/InP samples. One reason might be the comparatively low mobility of those samples.

In the following, we present a model, which qualitatively explains the different aspects of our observations. In the B range of a dissipationless regime, the bulk of the Hall bar is actually insulating. In the single-particle picture, if B is sufficiently high, each Landau level is split into two well-separated, spin-polarized levels with a degeneracy proportional to B. Therefore, a change in B will induce a redistribution of the electrons in the bulk of the Hall bar (denoted "bulk electrons") among the Landau levels, i.e. some electrons need to *have their energies changed and their spins flipped* in order to achieve equilibrium. However, as the bulk electrons have no effective interaction with the electrons at the edge nor with electron reservoirs (the ohmic contacts) in the dissipationless regime, the scatterings required to flip the spins and change the energies are virtually absent. The redistribution among the *single-particle* Landau levels is thus not possible. This means that the bulk electrons can be far from the "normal equilibrium" (the equilibrated distribution among the single-particle Landau levels) inside the dissipationless regime if B is changed. To the best of our knowledge, no study has been carried out on how these electrons redistribute in the energy and spin space in such a "nonequilibrium" situation. As it is not possible for the bulk electrons to redistribute among the single-particle Landau levels, effects such as electron-electron interactions must take place. We speculate that the real distribution maintains some order, which means that the electrons might rearrange to form "mini-gaps" and "mini-bands" in the energy and spin distribution.

When the 2DES starts to enter the dissipation regime where the bulk-edge interactions are still considerably weak, we expect the electrons in the mini-bands to be affected. Each time a mini-band starts to participate in the scattering process, a differential resistance peak is observed. In this picture, the multiple resistance peaks and fine structure reflect the mini-band structure of the nonequilibrium distribution of the bulk electrons. One may speculate that similar nonequilibrium distribution also forms in the *fractional* QHE regime [21], which might as well give rise to resistance peaks. If a strong current is applied to the Hall bar, the large Hall electric field will substantially enhance the interaction between the electrons at the edge and those in the bulk, and therefore give rise to much stronger and sharper resistance peaks, in agreement with our experimental observations. Note that the ranges of B in which the resistance peaks and fine structures are observed are only *slightly* away from the dissipationless regime. Therefore, the scattering between electrons in the bulk and electrons at the edge is expected to be rather weak. In addition, since the bulk area of a Hall bar is fairly large, the time constant of the equilibration can be very long, which explains the slow physical process indicated especially in Fig. 2. The details of the distribution of nonequilibrium electrons, and thereby the mini-bands, depend on the initial B position, the sweep direction, and the sweep speed. This thus explains the observed strong dependence of the resistance peaks and fine structures on the experimental history.

The observed NMR resistance peaks shown in the inset of Fig. 1(b) also supports our model. Via the hyperfine interaction an electron spin can flip with a simultaneous flop of a nuclear spin, which can be induced by, for example, applying NMR rf signals [22]. Because in our model the lack of electron spin-flip scatterings is the reason for the nonequilibrium distribution of bulk electrons, the additional electron spin-flip scattering induced by the NMR signals will reduce the degree of nonequilibrium distribution. This leads to an increased scattering probability from edge to bulk, which is detected as an increase of the resistance, as shown in the lower inset of Fig. 1(b). The threefold splitting is most likely caused by the electric quadrupole interaction, which is possible in our sample where large electric field gradients are expected. This connection to nuclear spins is in line with earlier observations of the importance of nuclear spin polarization in experiments on 2DES. The dynamical nuclear polarization has been observed as Overhauser shifts in electrically detected spin resonance experiments [23] and in e.g. the time dependency of current-voltage characteristics in transport experiments in which spin polarized electrons were injected [24–26]. Also, our results are, although performed in a different physical regime, similar to the recent findings in Ref. 20. This may imply that a similar scattering mechanism might be involved in the two different regimes.

To conclude, unexpected strong, ultra-narrow resistance peaks and fine structures have been observed in the regime of breakdown of the QHE. The studies reveal the involvement of a very slow physical process, which is not predicted by existing models. We also show a clear connection between the sharp peaks and the nuclear spin polarization. Furthermore, we have presented a model that emphasizes the important role of the nonequilibrium distribution of bulk electrons and qualitatively explains the observed phenomena.

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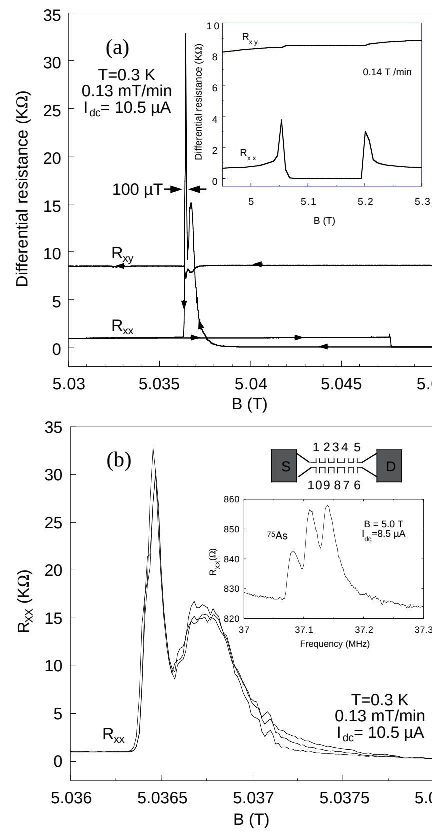

FIG. 1. (a) R_{xx} and R_{xy} as a function of B around $\nu = 3$ at $I_{dc} = 10.5$ μA. The sweep speeds are 0.13 mT/min (main curves) and 0.14 T/min (inset). (b) R_{xx} curves of a downward sweep from different segments of the Hall bar, which is shown in the upper inset. The lower inset shows an NMR resonance spectrum of ^{75}As. The applied dc current is 8.5 μA, with which a sharp R_{xx} peak is detected at 5.0 T. By fixing B at 5.0 T, however, we find that R_{xx} slowly decreases with time and after about 15 minutes becomes stabilized at about 825 Ω. By applying rf signal to a small coil around the sample, a clear threefold splitting is observed.

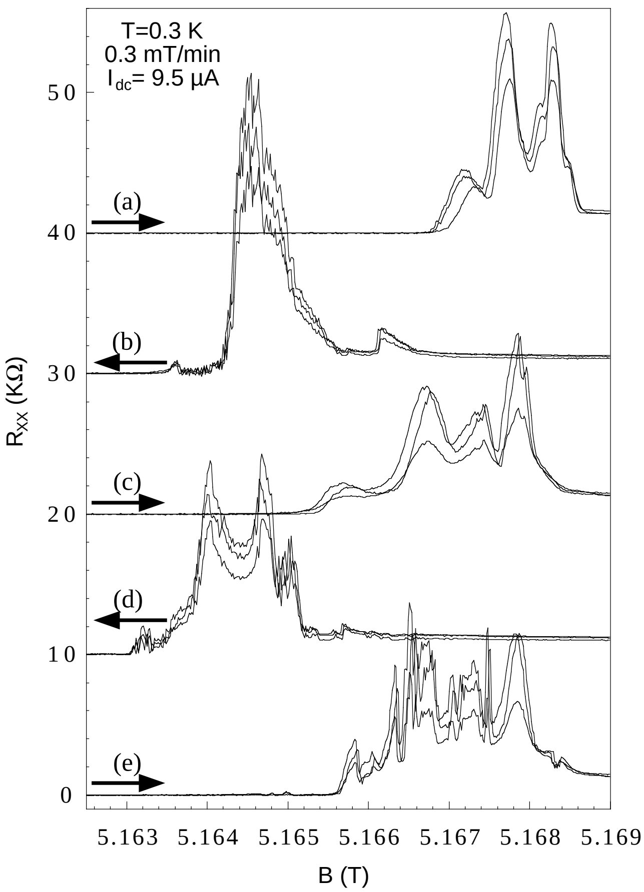

FIG. 2. R_{xx} traces obtained from different segments of the Hall bar at $I_{dc} = 9.5\ \mu$A and around the higher B edge of the dissipationless regime of $\nu = 3$. As it is a different cooling cycle, the peak position is lower than that shown in the inset of Fig. 1(a) although it should have been shifted towards a higher field because I_{dc} is lower. Five successive sweeps [(a)–(e), offset by 10 kΩ for clarity] are made back and forth at a speed of 0.3 mT/min. The arrows indicate the sweep directions.

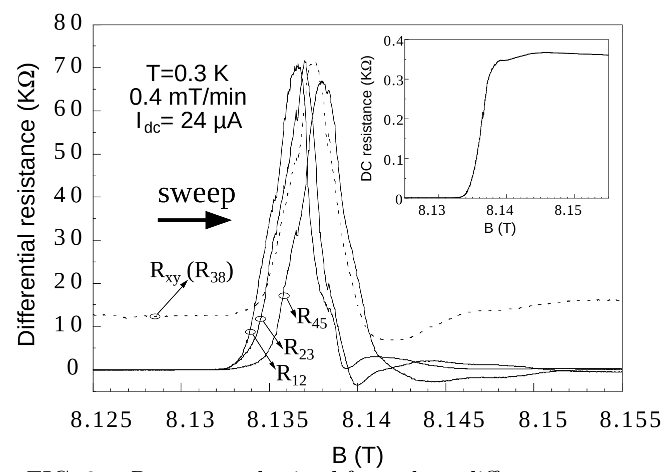

FIG. 3. R_{xx} traces obtained from three different segments of the Hall bar and one R_{xy} curve, at $I_{dc} = 24\ \mu$A and around the higher B edge of the dissipationless regime of $\nu = 2$. The inset shows a simultaneous measurement of the dc longitudinal resistance.